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Mass transfer of soil indoors by track-in on footwear

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Abstract

Inadvertent soil ingestion, especially by young children, can be an important route of exposure for many environmental contaminants. The introduction of exterior soil into the interior environment is a significant element of the exposure pathway. The unintentional collection of outside soil on footwear followed by subsequent deposition indoors is a principal route of soil ingress. Here we have investigated likely rates of dry and wet soil deposition on indoor hard surface flooring as a result of mass transfer from soiled footwear. In this pilot study, testing involved both single track-in events (with deposition resulting from a single progression of transfer steps) and multiple tracking actions (with deposition and dispersion resulting from repeated transfer steps). Based on soil mass recovery from the floor surface it was found that any contamination introduced by one-time track-in events was of limited spatial extent. In contrast, under repeated tracking conditions, with multiple soil incursions, widespread floor surface contamination was possible. Soil mass recovery was accomplished by brushing, by vacuum cleaner removal and by wet wiping. All the clean-up methods operated imperfectly and failed to remove all initially deposited soil. The level of floor surface soiling that resulted from the track-in tests, and the incomplete clean-up strongly suggest that under unrestricted transfer conditions rapid accumulation and dispersal of soil on indoor flooring is likely.

Keywords: Soil; Floor-dust; Contamination; Footwear; Tracking

1. Introduction

Indoor floor dust is a heterogeneous melange of organic and inorganic particulate matter (USEPA, 1997). This medium is composed of material that is derived from a variety of interior and exterior sources (Butte and Heinzow, 2002). From a human health exposure perspective, the presence of hazardous materials in indoor dust (e.g., heavy metals, pesticides) can be of considerable importance (Roberts and Dickey, 1995). Inadvertent ingestion of indoor dust by children through hand-to-mouth activity or inhalation following mechanical resuspension can be important routes of exposure.

A recognized common constant process by which indoor floor dust mass is accumulated is by mechanical transport (e.g., on footwear) of outdoor dust and soil (Fry et al., 1985; Cannell et al., 1987; Allott et al., 1994). A substantial fraction of indoor dust can be derived from outdoor soil. Estimates of the exterior soil contributions have been proposed in the ranges from 20–30% (Davies et al., 1985; Culbard et al., 1988; Rutz et al., 1997), to 30–45% (Fergusson and Kim, 1991; Trowbridge and

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Burmaster, 1997), and the United States Environmental Protection Agency (USEPA, 1994) uses (for modeling purposes) a default mass fraction of soil in indoor dust of 70% (M_{SD}=0.7). It has, however, been estimated that as much as 85% of indoor dust is from outside the home (Roberts et al., 1991). Such a contribution to indoor dust is important because soil and dust ingestion is common among young children. Daily intake is likely to be between 39 mg/day and 271 mg/day with an average of 138 mg/day, and 193 mg/day for soil and dust ingestion (USEPA, 2004). Exposure of this magnitude is of concern where outdoor soil and dust can be a vector for outdoor contaminants (Paustenbach et al., 1997). The introduction into the indoor environment of herbicides and pesticides applied outdoors is well recognized (Lewis et al., 1994, Nishioka et al., 1999, Lewis and Nishioka, 1999). Similarly, correlations between outdoor soil and indoor dust lead (Pb) levels (e.g., Thornton et al., 1990) are strongly suggestive of indoor transfer of metals in soils. The National Survey of Lead-Based Paint in Housing in the United States demonstrated that exterior soil Pb contributes (statistically) to indoor floor dust lead (USEPA, 1993). The importance of the relationship between outdoor soil, indoor dust and Children's blood Pb levels has also been amply documented in many epidemiologic studies (see Lanphear et al., 1998). The Pb contamination exposure pathway from soil to indoor dust has been documented through the application of structural equation models (Marcus and Elias, 1995), that have demonstrated that soil lead operating through dust Pb or dust on children's hands is an indirect influence of children's blood Pb at various sites (Succop et al., 1998). Measured reductions in indoor dust Pb levels following efforts to remove and control outdoor soil and dust Pb further demonstrate the importance of the track-in of metal contaminants (e.g., Von Lindern et al., 2003), as do reductions in pediatric blood Pb levels following outdoor soil abatement accompanied by a marked decrease in house dust Pb (Aschengrau et al., 1994).

Integral to assessments of the exposure threat posed by contaminated indoor dust derived from outdoor sources are questions relating to the degree and rate of mechanical incursion, residence time of deposited dust, and rates of removal. In this study we examine the fate of exterior soil tracked into the indoor environment. The focus is largely on initial indoor incursions. The interface between the exterior and the interior environment is an important one as it usually marks a rapid transition from one set of surface conditions outdoors (e.g., frequently heterogeneous and unconsolidated) to a quite different set indoors (e.g., homogenous and fixed with generally a different surface roughness). Concomitant with such abrupt change is an expected interruption in transport processes. Resulting failure of continued mass transport presents the possibility of rapid deposition and contamination. To investigate this, we conducted a pilot study comprised of a number of experiments aimed at assessing the likely rates of small-scale indoor deposition and dispersion of both dry and wet soil on footwear. Here, we used a direct soil mass deposition and recovery method. Unlike indirect tracing techniques, which focus on a specific exogenous component of the medium, such as those that use a fluorescent tracer (e.g., Cannell et al., 1987) our approach reports on actual particle dispersal and is not particle size or density dependent. Like other tracing methods, our approach is limited by the amount of material that can be measured after deposition (the method detection limit). The dust recovery method we have used is limited by the mass of material that can be detected gravimetrically on the collection medium.

In addition to dry soil, wet soil track-in was assessed as it is recognized that indoor floor dust loadings can increase in wetter weather conditions due to wet dirt and soil track-in (Al-Radady et al., 1994; Petrosyan et al., 2006), and this effect may account for elevated indoor loadings in winter months in regions with cold wet conditions without continuously frozen, snow-covered, ground (Laxen et al., 1988). Even in regions with significant snow seasons, at wet transitional times (preceding and succeeding the winter moths) indoor loadings can increase due to wet soil and dust track-in, which may even occur during the winter months due to contaminated snow track-in (Yiin et al., 2000). All of the tests in this study involved unrestricted transfer in that once soil was adhering to a shoe's sole no initial efforts were made to reduce the soil loading (e.g., by wiping on an entrance mat). The study also examined the effect of different sole types on deposition and dispersal (smooth versus tread pattern soles). In addition, we evaluated the relative effectiveness of different mechanical removal mechanisms, by comparing vacuum (cleaner) removal with brushing and wet wiping. The flooring surface of choice in this study was typical hard surface vinyl floor tiling.

2. Materials

Tracking experiments with wet and dry soils employed sub-samples of a composite surface soil from Syracuse, NY. This composite soil consisted of an amalgamation of over 150 samples of urban yard soil collected during a previous investigation (Johnson and Bretsch, 2002). As 79% of the U.S. population reside in urban areas (U.S. Census Bureau, 2000), it was deemed appropriate to use a representative urban soil to investigate soil track-in processes. Prior to use, the composite soil was air dried, ground, and screened through an 85 μm nylon mesh. For the wet soil tracking experiments, the soil was prepared as a slurry. A wet-mud-like consistency for the soil was achieved after several tests. A mixture of 2 g of test soil and 2 ml of water produced a wet paste with a non-pourable consistency. This volume-to-mass ratio was used for each wet soil track test.

Deposition tests involved two (shoe) sole types: a flat, smooth leather sole and a rubber sole with a fine tread (U.S. size 11). Both sole types were used in both the wet and dry soil tracking tests to identify any major variations in soil retention by such different sole types. The tests were conducted with 12″ × 12″ Armstrong® vinyl floor tiles. In no test was the same tile set used more than once.

The mass of soil deposited in each experiment was determined gravimetrically. Deposited soil recovery for mass determinations was either by wet-wiping, vacuuming or brushing. These removal methods were chosen to provide some comparison of the likely efficiency of clean-up methods typically used to remove deposited surface dust from residential flooring. Wet wiping of tile surfaces employed commercially available Ghost Wipes®. These wipes, each consisting of 15 cm × 14 cm squares of cross-linked polyvinyl alcohol material, meet all ASTM E1792 specifications for sampling materials for Pb in surface dust and OSHA Methods ID-125G. Wet wiping is probably the most widely used method of sampling indoor surfaces for dust borne contaminants (e.g., HUD, 2001). Here, wet wiping removal of material from a tile surface was accomplished by following a modified version of the ASTM E1728-02 wiping methods. The same pattern of surface wiping was used across the entire surface of a tile but repeated until the tile surface visually appeared free of deposited soil. In some instances (depending on the test or the loading of deposited soil), multiple wipes were used on an individual tile. To determine the mass of soil recovered, each wipe was initially dried overnight at 60 °C, set aside to equilibrate in the lab for a minimum of three days, and then pre-weighed. Prior to wipe recovery each wipe was wetted with distilled water and after sampling was again dried and weighed. The laboratory dry and wet bulb temperatures were measured during pre- and post-sampling weighing and a relative humidity correction factor was applied before determining the recovered soil mass by difference. Vacuum removal of dust employed a non-commercial test vacuum cleaner. This employed a modified General Electric vacuum cleaner motor and blower assembly (Model AVF28) with dust collection following the method of Watt et al. (1983) using a pre-weighed Whatman 25 mm × 80 mm single thickness extraction thimble (nominal pore size ~10 μm). A 1/2″ Bel Art tubing connector "T" with an inlet ~3.5 mm × 62 mm with a face velocity of ~225 cm per second was used as the nozzle for sampling. Brushing removal was accomplished using a hand-held, stiff bristle brush. A stiff bristle hand-brush was chosen to affect the most complete (mechanical) removal of dried soil from the tile surface. Brush removed soil was collected on pre-weighed glassene paper. Brushing was continued until no more soil could be removed from the tile.

3. Methods

The wet soil deposition tests were designed to simulate the immediate indoor shoe-to-floor transfer of wet soil from a single ingress event. These tests were conducted with eight floor tiles. The tests involved the application of a (subsequently) known mass of wet soil to the sole of a test shoe. Each shoe was then walked across four tiles. At the start of a test the wet soil (prepared in a mixing bowl) was pasted evenly by spatula over the entire toe area of a shoe sole. The wet soil was not applied to the heel or the instep of the shoe. To assess the mass deposition per tile in each test approximately 2 g of wet soil was prepared for application to the shoe sole. Following each test, any soil that remained in the mixing bowl was recovered to determine the mass of soil not applied to the shoe sole. In addition, any soil adhering to the sole of the shoe on completion of the test was washed off and filtered through a pre-weighed Whatman qualitative filter. The mass of filtered soil was determined following overnight drying and room temperature equilibration. With the exception of two track tests, deposition was initiated immediately after the wet soil was applied to the sole of the shoe. In the final two tracking tests (with smooth soled shoes), the wet soil was allowed to dry on the sole for approximately one minute until the wet sheen on the wet soil vanished. The wet deposition test was replicated eight times (twice with each sole type).

The dry soil deposition tests were conducted with two sets of five tiles that provided separate deposition surfaces for right and left shoes. For each single track-in test approximately 10 g of soil was evenly spread across a plastic tray simulating an exterior source of dry friable soil. At the start of each test both right and left shoes were pressed (under the weight of the tester) into the test soil to acquire a coating of dry soil on the sole and heel of each shoe. After this one-time coating of the soles, each shoe was trodden in sequence on each of the assigned five tiles. Following each test, any soil adhering to the sole of the shoe was washed off and filtered through a pre-weighed qualitative filter. The mass of filtered soil was determined following overnight drying and room temperature equilibration. The dry deposition test was replicated four times (twice with each sole type). Soil recovery from tiles was accomplished by both wet wiping (following track-in tests using smooth and treaded soles) and vacuum removal (after the other smooth and treaded sole track-in tests).

To assess the spatial distribution of track-in dry soil following multiple tracking events with multiple incursions of dry soil, a similar experimental set-up as the single track-in of dry soil test was employed. The test was designed to simulate the repeated tracking across a tile floor room following multiple introductions of soil on footwear from the outdoor environment. A pristine set of one hundred pre-cleaned floor tiles was arranged in five adjacent/touching columns of twenty tiles. The center column of 20 tiles was designated the primary deposition ("walk-on") surface that was traversed by the tester. The columns of tiles on either side served as a deposition surface for dry soil laterally displaced during the tracking tests. The tester did not come into contact with these adjacent tiles during the experiment, and considerable care was taken to confine foot placement within the tile area and to accurately replicate the designated step sequence throughout the experiment. The initial test soil sample (approximately 10 g) was spread across a plastic tray large enough to accommodate the test footwear. At the start of the experiment the tester stood on the tray and ground the sole of the shoe into the dry soil to simulate collection of dry soil of the shoe in the outdoor environment. The test then involved the tester walking along the center column of tiles, alternating between tiles with each footfall. In the first pass (forward), the tester trod on 10 tiles (5 right and 5 left footfalls). An alternate step pattern was employed that involved a right then left foot sequence with intervening tiles stepped over (to simulate a natural stride pattern). At the end of the first forward pass the tester pivoted on tile 20 and then made a return pass stepping on the alternate tiles not stepped on during the forward pass. At the end of the return pass, the tester pivoted on the first tile then repeated the forward pass. Each forward and return pass was repeated 10 times. Upon completion of the tenth return pass approximately 1 g of dry soil was added to the initial soil reservoir, and the tester once more stepped onto the soil and ground the footwear into the soil. The 10 forward and 10 return pass sequence was then repeated. In all, this operation was repeated five times with intervening soil pick-ups on each occasion. On completion of the test, the soil on each of the 100 tiles was recovered using separate Ghost wipes (two wipes were used for each of the center "walk-on" tiles).

Following gravimetric analysis of the Ghost wipe samples recovered from the multiple tracking, the wipes (120, plus 18 blank wipes) were subject to wet ashing and subsequent element analysis by inductively coupled plasma optical emission spectroscopy (ICP-OES). The acid digest involved adding 5 ml of concentrated nitric acid and 5 ml of distilled water to each wipe followed by boiling to dryness. Each sample was then re-suspended with 20 ml of 10% nitric acid and 5 ml of 30% hydrogen peroxide and heated for a further 20 min. Samples were gravity filtered through VWR® 410 qualitative filters and made up to 25 ml volume with 10% nitric acid. Element concentrations were measured on a Perkin Elmer Optima 3300DV OES instrument. Calibration and quality control standards (10% of the analytes) were made up from commercially available primary standards. Element data was recorded as tile loadings (quantity of element obtained from each tile) following the subtraction of the (average) blank wipe value from each test wipe value. An element detection limit was set at three times the standard deviation of the blank wipe values. At this level of detection, several of the measured elements (Cu, Zn, Ba, Ca) were only reportable for the wipes from the "walk-on" column of tiles, and were not subsequently included in the summary results.

The individual particles in the test soil were characterized by automated scanning electron microscopy (SEM) and X-ray energy spectroscopy (EDX). This technique provides data on the size and elemental composition (X-ray spectral data) of a statistically significant number of microscopic particles in a sample. This analysis was carried out using an ETEC Autoscan SEM operating in tandem with a Advanced Research Instruments (ARI) AutoSEM Image Analysis System and a Kevex 7500 X-ray Spectrometer (Johnson, 1983). During the analysis, 16 elemental regions of interest and 32 background regions for net X-ray relative intensity computations were assigned within the X-ray spectrum. The fraction of individual particle mass contributed by the detected elements was defined by the X-ray relative intensity times the estimated particle volume (assumed to be a prolate ellipsoid rotated about the long axis). This was weighted by the common molecular form of occurrence for each element in the soil (Johnson et al., 1981).

4. Results

In the wet soil deposition tests, between 1.5 g and 2 g of soil was consistently applied to each sole (Table 1). The subsequent track-in tests demonstrated that the amount of wet soil deposited from the shoe soles decreased with each successive step. Recovery of soil mass from each successive tile in each experiment revealed a consistent deposition pattern. This is illustrated in Fig. 1,

Table 1
Mass of wet soil applied to shoes and subsequently deposited onto test tiles during the tracking tests

Track test		Track-in soil mass (in grams) distribution		
		Mass on sole	Mass deposited	Mass left on shoe
Treaded sole vacuum removal	Right	1.922	0.507[a,b], 0.699[b] (26.3%, 36.4%)	0.716 (37.3%)
	Left	1.541	0.419[a], 0.492[b] (27.2%, 31.9%)	0.629 (40.8%)
Treaded sole vacuum removal	Right	1.634	0.454[a], 0.620[b] (27.8%, 37.9%)	0.561 (34.3%)
	Left	1.677	0.408[a], 0.524[b] (24.3%, 31.2%)	0.746 (44.5%)
Smooth sole brush removal	Right	1.537	0.957[c], 0.154[d] (62.3%, 10.0%)	0.426 (27.7%)
	Left	1.645	0.815[c], 0.242[d] (49.5%, 14.7%)	0.588 (35.7%)
Smooth sole brush removal	Right	1.632	0.305[c], 0.259[d] (18.7%, 15.9%)	1.068 (65.4%)
	Left	1.676	0.487[c], 0.217[d] (29.1%, 12.9%)	0.972 (58.0%)
Mean (range)		1.658 (1.541–1.922)	0.945 (0.564–1.206)	0.713 (0.426–1.068)

[a] Soil mass initially removed from tiles by vacuuming.
[b] Soil mass recovered by wet wipe from tiles following vacuum removal.
[c] Soil mass initially removed from tiles by brushing.
[d] Soil mass recovered by wet wipe from tiles following brushing removal.

which plots the percentage of the total applied mass on each sole that was subsequently deposited on each of 4 successive tiles. By the fourth tile only a small amount of the wet soil initially adhering to the sole was deposited. Despite this rapid drop off in the mass of wet soil deposition it is clear that a substantial proportion (between 34 and 65%) of the initially applied wet, but rapidly drying or dry soil, remained on the sole after the four steps (Table 1). Presumably, under real world conditions, some fraction of this adhering soil would subsequently be removed with further drying and flexing of the sole or by abrasion with other types of surface (e.g., carpeting). From Fig. 1 it appears that, irrespective of shoe sole type (smooth or treaded), unless the soil has dried on the sole (Fig. 1g and h), approximately the same amount of the wet soil mass applied in each experiment was deposited at the first step. The observed differences in the first step deposited masses were only apparent when the applied wet soil was allowed to dry slightly. These variations in percentage of soil mass deposited became less pronounced at the second step. At the second, third and fourth steps the differences in percentage of soil mass deposited differed minimally between experiments.

In the four dry single track-in deposition experiments variable masses of soil were picked-up on the test shoes. Based on the sum of the soil masses recovered from the tiles and from the soles of the shoes (on completion of the tracking), approximately 0.72 g (range 0.39–1.03 g) of dry soil was picked up by each shoe (Table 2). Between 34 and 86% of the picked-up mass was deposited from each shoe across the test tiles. The rate of deposition on each tile is represented graphically in Fig. 2. In each test, the amount of dry soil deposited decreased on successive tiles. In each test by the last tile (fifth in the sequence) less than 10% of the total deposited mass was left on the tile. However, the rate of deposition differed between sole types. Dry soil retention on the smooth soled shoes (Fig. 2e, f, g, h) was, perhaps counter-intuitively, greater than that of the treaded soles.

Soil mass recovery from the dry soil repeat tracking test (simulating repeated tracking interaction after repeat

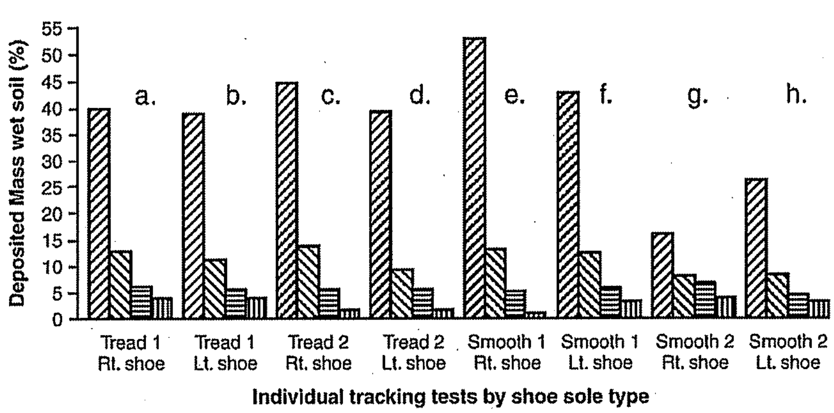

Fig. 1. Wet soil deposition following tracking across a sequence of four floor tiles (tile 1: ▨, tile 2: ▧, tile 3: ▤, tile 4: ▥) following duplicate pick-up tests for both right (Rt.) and Left (Lt.) treaded (a, b, c, and d) and smooth soled (e, f, g, and h) shoes.

Table 2
Mass of soil picked-up on shoes and subsequently deposited onto test tiles during the dry-soil tracking tests

Track test		Track-in soil mass (in grams) distribution		
		Mass picked-up	Mass deposited	Mass left on shoe
Treaded sole wipe removal	Right	0.664	0.562 (84.8%)	0.102 (15.2%)
	Left	0.805	0.688 (85.5%)	0.117 (14.5%)
Treaded sole vacuum removal	Right	0.726	0.515[a], 0.017[b] (70.9%, 2.3%)	0.194 (26.7%)
	Left	0.431	0.262, 0.012 (60.8%, 2.8%)	0.157 (36.4%)
Smooth sole wipe removal	Right	1.034	0.759 (73.4%)	0.275 (26.6%)
	Left	0.832	0.525 (63.1%)	0.307 (36.9%)
Smooth sole vacuum removal	Right	0.386	0.153, 0.010 (39.6%, 2.6%)	0.223 (57.8%)
	Left	0.871	0.373, 0.012 (32.8%, 1.4%)	0.486 (55.8%)
Mean (range)		0.719 (0.39–1.03)	0.486 (0.16–0.76)	0.233 (0.10–0.45)

[a] Soil mass initially removed from tile by vacuuming.
[b] Soil mass recovered by wet wipe from tile following vacuum removal.

contamination events) demonstrated a decrease in deposition with tracking progression across the sequence of tiles (Fig. 3). However, the reduction in deposited soil mass with tracking distance was far less marked than in the case of the single track of dry soil. In no instance was the mass of soil on the last tile in the sequence less than 25% of the mass deposited on the first tile in the "walk-on" tile sequence. Measurable soil mass was also recovered from the column of tiles immediately adjacent to the primary deposition column, but not from the two distal columns of tiles. Of the deposited soil mass (recovered from the central 60 tiles), approximately 9% was recovered almost equally from each of the two columns of tiles adjacent (at left and right) to the center column (Fig. 3a and c). The bulk of the deposited soil mass (82%) was recovered from the "walk-on" tiles (Table 3). This recovery process did not account for all the soil dispersed across the testing surface; it is likely that discoloration of the wipes from the tiles on the periphery represented additional soil dispersion even though the mass could not be detected gravimetrically. Some indication of the lateral dispersion onto these peripheral tiles was provided by the compositional data from the chemical analysis of the tile wipes. Summaries of the tile loadings for the elements Fe, Mn and Pb are set out in Table 3. Major soil elements such as Si and Al have not been reported because of limited mobilization by the nitric acid digest, and data for other more available elements (e.g., Zn and Cu) have not been included because of high blank wipe concentrations. The individual element loadings along the central "walk-on" tiles showed the same distribution as the soil mass deposition (Fig. 3b). The lateral distribution of the element loadings across the tiles was also similar to the soil mass distribution. Of the total tile loading, approximately 90% was from the center column of "walk-on" tiles, 4% was from the two immediately adjacent columns of tiles, and 1% from the two peripheral columns of tiles. The averaging of the tracked soil mass along the primary deposition tiles in addition to the marked lateral distribution of the soil mass along the rows of tiles strongly suggests that the repeated stepping on the tiles led to extensive spatial re-distribution of the soil. The element loading findings of measurable distal lateral deposition confirmed marked sideways dispersion of the (potentially hazardous) soil components. The difference in soil mass and element loading distribution may be attributed to differences in the particle size associations of the different elements. Based on automated SEM analysis of particles from the <85 μm Syracuse test soil (Table 4), the abundance of Si was found to increase

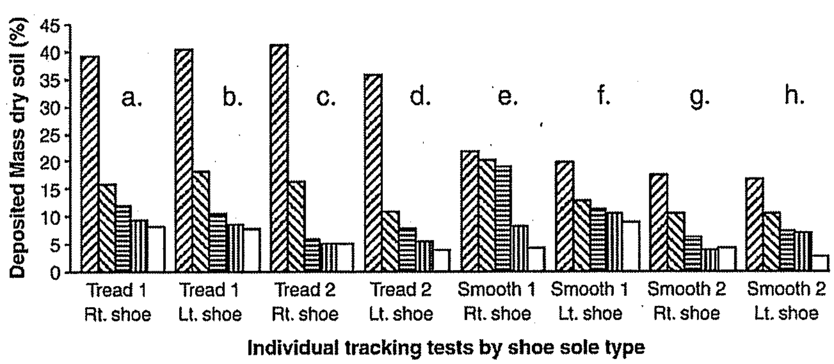

Fig. 2. Dry soil deposition following tracking across a sequence of five floor tiles (tile 1: ▨, tile 2: ▧, tile 3: ▤, tile 4: ▥, tile 5: □) following duplicate pick-up tests for both right (Rt.) and Left (Lt.) treaded (a, b, c, and d) and smooth soled (e, f, g, and h) shoes.

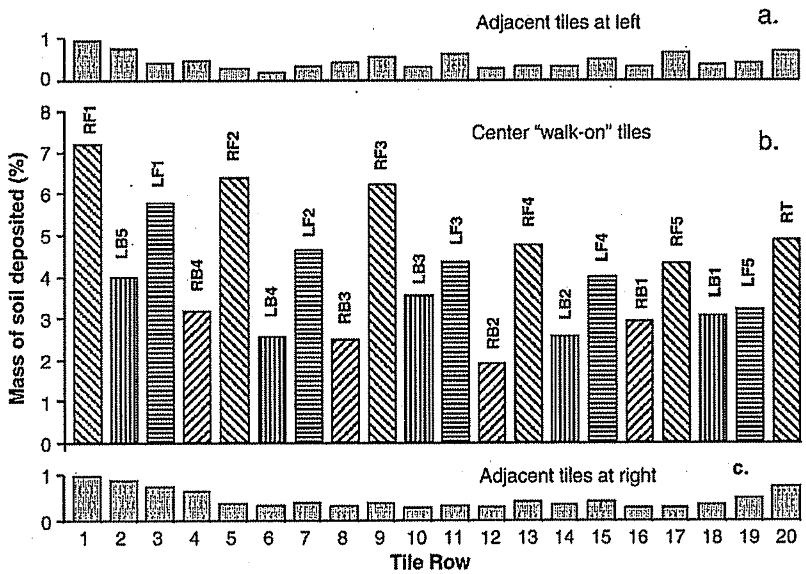

Fig. 3. Percentage mass deposition on repeat tracking tiles (b) following multiple incursions of dry soil and on neighboring tiles to the left (a) and right (c) of the tracking tiles (R = right shoe, L = left shoe, F = forward, B = back, T = turn).

with increasing particle size while that of Al, Fe, Mn, and Pb increased with decreasing particle size. We ascribe this to a dominance of quartz grains among the larger particles and a greater association of the other elements with the smaller (clay sized) soil particles. While data was not available on tile Si loadings, nor on the size of particles recovered from the tiles, we posit that the finer soil particles were likely more readily distributed away from the primary deposition tiles than the coarser soil particles.

Under the experimental conditions in this study with a test vacuum cleaner that did not employ a brush, vacuum removal of initially deposited wet soil, but subsequently dried *in situ*, was less effective than the hand brush. Vacuum collection only removed approximately 50% of the deposited mud (Table 1). Vacuum cleaner removal relied largely on mechanical agitation with the vacuum head to dislodge the dried soil. This mechanical breakup was less efficient that the brush removal of the soil. The vigorous brushing of the dried soil removed much more from the tile surface; however, after brushing approximately 15% of the soil still adhered to the surface. Vacuum cleaner removal of dry deposited soil was much more effective and in no instance was more than 3% of the soil mass left on a tile following vacuuming (Table 2). In

Table 3
Tile soil mass and element loadings for soil deposited *in situ* and distributed laterally onto test tiles during the repeat dry-soil tracking test

Test tiles	Soil mass and select elements deposited (%)			
	Soil mass (%) [tile range]	Fe loading (%) [tile range]	Mn loading (%) [tile range]	Pb loading (%) [tile range]
Column at far left	ND[a]	0.283 mg (0.9%) [0.008–0.017 mg]	7.78 μg (0.9%) [0.23–0.53 μg]	2.48 μg (0.5%)[b] [<0.31–0.41 μg]
Column at left	0.231 g (9.0%) [0.007–0.024 g]	1.340 mg (4.1%) [0.027–0.155 mg]	37.12 μg (4.2%) [0.74–3.62 μg]	20.16 μg (4.2%) [0.31–2.28 μg]
Center tiles (walked-on)	2.101 g (81.8%) [0.049–0.185 g]	29.516 mg (90.2%) [0.958–2.652 mg]	784.23 μg (89.7%) [24.92–68.43 μg]	436.86 μg (90.9%) [13.91–38.16 μg]
Column at right	0.237 g (9.2%) [0.007–0.025 g]	1.263 mg (3.9%) [0.027–0.139 mg]	35.70 μg (4.1%) [0.23–0.53 μg]	20.34 μg (4.2%) [0.36–2.25 μg]
Column at far right	ND	0.328 mg (1.0%) [0.009–0.023 mg]	9.26 μg (1.1%) [0.25–0.70 μg]	3.1 μg (0.7%)[c] [0.32–0.51 μg]

[a] None detected (ND).
[b] Sum of loadings from 8 of 20 tiles with Pb = detection limit of 0.31 μg per tile.
[c] Sum of loadings from 7 of 20 tiles with Pb = detection limit of 0.31 μg per tile.

Table 4
Select element percentages for size fractions of <85 μm Syracuse test soil based on automated scanning electron microscopy analysis (at 70×) of individual soil particles

Particle size[a]	Number of particles	Element percentage per size fraction				
		Si	Al	Fe	Mn	Pb
>32 μm	53	31.93	3.57	3.91	0.15	0.06
16–32 μm	264	27.60	4.06	4.68	0.16	0.06
8–16 μm	1251	25.70	5.25	6.24	0.22	0.08
4–8 μm	1620	24.85	6.33	6.73	0.20	0.11
1–4 μm	88	23.00	6.33	6.85	0.26	0.13

[a] Area equivalent diameter of the particle projected image.

contrast, wet wiping, which was used as either the primary deposited soil recovery method, or as a follow-up to vacuum or brushing removal, visually appeared to be the most successful of the recovery methods. However, the wiping protocol that was used, which was developed for applications such as clearance testing (to assess dust contamination levels after removal of indoor Pb-based paint) and sampling, is not completely suited for wipe clean-up. This was evident from the need to use multiple wipes on the heavily contaminated wet soil deposition tiles. Heavy loading on the individual wipes required the use of two or more wipes per tile to effect complete removal of the generally greater than half a gram of soil per tile remaining after vacuuming (Table 1).

5. Discussion

The data from the wet soil deposition tests suggest that the deposition of wet soil occurs relatively rapidly upon the initiation of tracking. Wet mud on the shoe soles no longer posed an immediate deposition hazard after 5–6 steps across a deposition surface. This implies that mud tracking after the initial ingress into an indoor environment is spatially limited. Interestingly, a substantial amount of soil (typically equivalent in mass to that deposited at the first step) was still adhering to the shoe at the completion of the test. While this mass was no longer subject to immediate deposition, under real world conditions it may pose a deposition/exposure risk at some later time in the indoor environment.

Results from the single ingress dry soil track-in tests indicate that the transfer of dry soil onto the soles of shoes is limited. Typically no more than 1 g of dry soil was picked-up irrespective of the sole type. However, the rate of post pick-up deposition varied between sole types. In these tests, a greater proportion of the adhering dry soil was rapidly lost from the treaded sole. Irrespective of the irregular deposition pattern between sole types by the last test tile, less than 10% of the pick-up mass was being deposited. However, a significant portion of the pick-up soil was retained on the sole after the initial incursion and this fraction will inevitably be deposited at some subsequent point. The rapid deposition of most of the dry soil mass suggests that during a single track-in incursion most of the adhering soil is laid down close to the point of ingress. In terms of impeding contamination of the indoor environment early trapping of sole-bound soil is likely to be highly effective.

The rates of deposition observed here in the single track-in tests on hard surface flooring are consistent with those observed elsewhere. Cannell et al. (1987), using a fluorescent tracer to assess mass deposition during indoor tracking, similarly found that within 4–5 steps after ingress mass transfer from footwear was complete. The rapid deposition upon the initiation of tracking observed here for hard surfaces has similarly been found in studies with carpeted surfaces (Cannell et al., 1987; Roberts et al., 1996). However, in these latter studies it appears that the loss of adhering soil mass to carpeting happens more immediately (within 2–3 steps).

The soil mass distribution resulting from multiple soil incursions in association with repeated tracking is very different to the pattern produced by the single dust incursion followed by a single track-in. The multiple tracking exercise produced substantial dispersal of soil across the contact tiles. The less marked (although still obvious) trend in the reduction in the amount of dry soil deposited across the tile progression likely reflected a forward distribution (along the tracking path) of the soil following repeated soil pick-up and drop-off events. This re-entrainment phenomenon is an important mass transfer process. Soil mass recovery, and element loadings, from the columns of (not trodden on) adjacent tiles attest to a resuspension process that caused an aerosolization and lateral dispersion of the dry soil. From such a lateral distribution it is not unreasonable to conclude that the process also produced a degree of backward and forward re-distribution. This probably accounted for the increase in deposited mass at the end of the tile sequence (spreading from the tiles at the beginning of the sequence), and likely added to the averaging of the deposited soil across the tile sequence.

The dominance of soil mass deposition along the main tracking path reinforces observations made elsewhere of the importance of high traffic areas indoors as sites of elevated dust contamination (e.g., Allott et al., 1992). Thatcher and Layton (1995) found that dust mass accumulation on frequently tracked areas of flooring in a residential property far exceeded the accumulation on untracked areas. Their study also found that mass accumulation on tracked areas at locations remote from the property entrance (on the second story) was also less. Similarly, Nishioka et al. (1999), in a study aimed at measuring indoor levels of herbicide 2,4-Diclorophenoxyacetic acid after a lawn application, found that the levels indoors usually followed a gradient (with a maximum at the entrance) that matched the traffic pattern through the home that the residents followed when entering from outdoors.

Soil clean-up success differed markedly between procedures. Brushing and vacuum cleaner removal of (wet deposited) dried soil were clearly less effective than wet wiping. Neither aggressive brushing, nor agitation with the vacuum head, provided sufficient mechanical abrasion to dislodge all the "dried-on" soil. In contrast, vacuum cleaner removal of dry deposited soil was much more effective than vacuum removal of *in situ* dried soil. However, the adhesion forces binding the dry deposited soil particles to the tile surface were sufficient to retain a measurable amount of soil mass. Vacuum collection can be highly variable depending on the method and the media conditions (Byrne, 2000).

Wet wiping was viewed here as the most effective clean-up method; however, it was found not to be totally efficient. Visual inspection indicated that wet wiping was successful at collecting the soil adhering to the tile surface, but additional microscopic examination demonstrated that dust recovery was not complete. This is illustrated in Fig. 4, which documents the microscopic appearance of a pristine and cleaned tile surface after an initial deposition of wet soil (Fig. 4a), and then after multiple (ten) depositions of wet (slurry) soil with intervening wet wiping (Fig. 4b). In this test wet soil was repeatedly deposited by pipette onto the tile surface, allowed to dry, and then wet wipe removed (until the surface was visibly clean). It is apparent that despite wet wiping many small particles are present on the tile surface at the end of the test. The difference in particle size between the initial deposited soil and the post wiping residue suggests that the smaller soil particles have been preferentially retained on the tile surface. This may be a function of size selective wipe removal (i.e., wet wiping favoring coarse particle pick-up), and/or micro-topography trapping. During the wiping process, some of the surface particles may have been too small to be picked-up by the wipe; however, the appearance of the post wipe surface strongly suggests that the majority of retained particles are trapped in micro-scale crevices. It may be the case that particle retention under these test conditions was facilitated by the wiping process. The obvious surface asperities on the post-wiping tile, which were not present on the initial deposition tile, is suggestive of tile surface modification (forming wrinkling) during repeated wetting and drying.

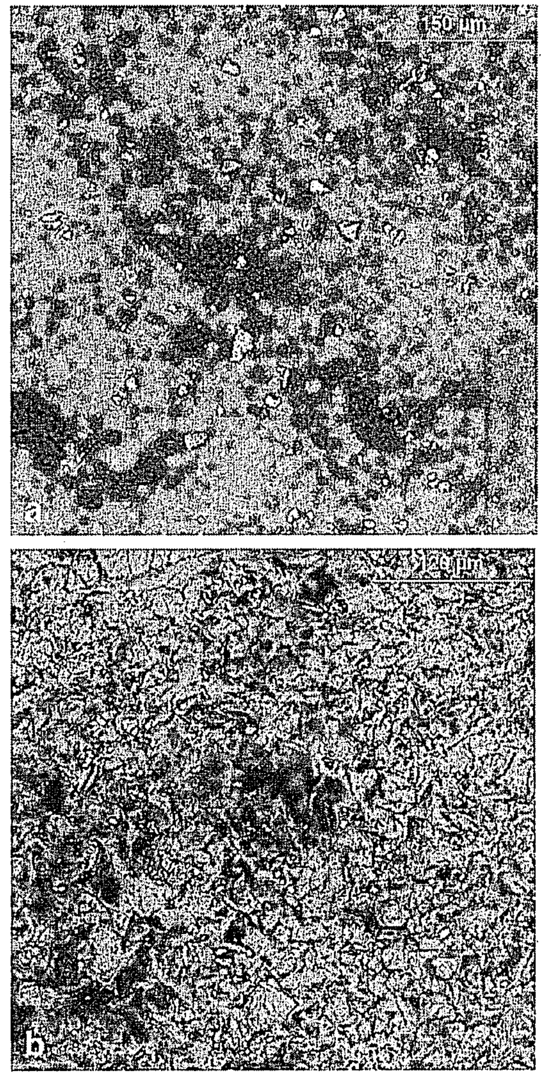

Fig. 4. Electron micrographs of contaminated tile surface after initial soil particle (bright objects) deposition (a) and following wipe removal of soil after several deposition events (b).

Vacuum cleaner removal of floor dust, particularly for soiled carpeting, has been recommended by various studies (Roberts et al., 1999; Yiin et al., 2002). The post-vacuuming surface retention of soil mass as described here is consistent with the results of trials aimed at reducing Pb dust loadings on hard flooring surfaces in residential properties. Rich et al. (2004) found that using vacuum cleaner removal of floor dust with follow up detergent and water cleaning resulted in an incomplete removal of the surface Pb content, confirming the resistance of dust to complete removal. Surface dust retention may also in part account for the "multiple sources of sample loss" attributed to vacuum sampling (Farfel et al., 1994).

6. Conclusions

Single incursions into the indoor environment of wet or dry soil adhering to footwear appear to lead to heavy, yet fairly limited, spatial contamination of hard surface flooring. With most of the deposited test soil being set down within the first 5 strides, initial soil contamination is likely to be limited to an area within 7–8 m of the entrance (given an average stride length of approximately 1.5 m). Despite such initial deposition, soil that remains adhering to the footwear may be substantial, and the potential exists for subsequent significant soiling elsewhere indoors following other removal events.

Repeated tracking of dry soil across hard flooring surfaces leads to a substantial re-distribution of the soil across the surface. This process clearly has the ability to create widespread contamination of the indoor environment. This will occur not only by repeated soil pick-up and deposition during the tracking process, but by a process of lateral displacement. The mechanical interaction between footwear, soil, and flooring that leads to soil aerosolization and lateral re-distribution results in distal parts of a floor, that are not directly affected by the track-in activity, becoming contaminated.

Track-in simulations furnish data on the quantities of soil conveyed indoors upon initial ingress. Estimated deposition rates provide basic inputs for indoor exposure models, and dose calculations. However, the magnitude of external soil contributions may be modulated by any of a number of factors. The number, age structure, and habits of the occupants are important modifiers. Similarly, differences in floor covering, variations in activity patterns, and the frequency and effectiveness of the cleaning practices, are important controls on subsequent indoor redistribution. It is anticipated that in our future work the impact of such variables will be addressed. Based on this pilot study, before-and-after simulations are envisioned that factor in the movement of children (in specific age ranges), and adults engaged in unrestricted movements within mock-up residential spaces.

The clean-up of dry and wet deposited soil from hard surface flooring appears to be more effectively accomplished using wet wiping methods rather than mechanical removal (e.g., by vacuuming or brushing). However, none of the tested removal techniques seems capable of fully eliminating all post-deposition residual soil particles. With some soil particles retained *in situ* after removal efforts, in some instances an un-recognized post-cleaning exposure threat may remain on hard surface flooring. Such a hazard is probably of most concern in situations where the exposure risk is direct, such as in the case of crawling infants with repeated hand contact with the floor. In some circumstances the problem may be compounded by the size selective nature of clean-up removal. It is recognized that detachment forces, of the type involved in vacuum removal, are dependent on particle mass, and that smaller particles exhibit greater resistance to removal (Corn, 1961). So, the enrichment of a pollutant in the finest particle sizes, which is the case for many metals in soils (e.g., Spittler and Feder, 1979; Dong et al., 1984; Qian et al., 1996), and for pesticides in indoor dust (Fortune et al., 2000), may lead to an elevated surface loading. This would be facilitated by the preferential track-in of finer sized soils and dusts (Allott et al., 1992). An obvious concern is that repeated cleaning may lead to a pollutant build-up, and any received dose will not be diluted by a coarse particle component because coarse material has been preferentially removed with cleaning. Moreover, the risk would possibly be exacerbated by the fact that finer sized particles are more likely to adhere to the hand (Driver et al., 1989).

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References

Allott RW, Kelly M, Hewitt CN. Behavior of urban dust contaminated by Chernobyl fallout: environmental half-lives and transfer coefficients. Environ Sci Technol 1992;26(11):2142–7.

Allott RW, Kelly M, Hewitt CN. A model of environmental behaviour of contaminated dust and its application to determining dust fluxes and residence times. Atmos Environ 1994;4:679–87.

Al-Radady AS, Davies BE, French MJ. Distribution of lead inside the home: case studies in the North of England. Sci Total Environ 1994;145:143–56.

Aschengrau A, Beiser A, Bellinger D, Copenhafer D, Weitzman M. The impact of soil lead abatement on urban children's blood lead levels: phase II results from the Boston Lead-In-Soil Demonstration. Environ Res 1994;67(2):125–48.

Butte W, Heinzow B. Pollutants in house dust as indicators of indoor contamination. Rev Environ Contam Toxicol 2002;175:1-46.

Byrne MA. Suction methods for assessing contamination on surfaces. Ann Occup Hyg 2000;44(7):523–8.

Culbard EB, Thornton I, Watt JM, Wheatley M, Moorcroft S, Thompson M. Metal contamination in British urban dusts and soil. J Environ Qual 1988;17(2):226–34.

Cannell RJ, Goddard AJH, ApSimon HM. Contamination of dwellings by particulate matter: ingress and distribution within the dwelling. Radiat Prot Dosimetry 1987;21:111–6.

Corn M. The adhesion of solid particles to solid surfaces I: A review. J Air Pollut Control Assoc 1961;11:566–75.

Davies BE, Elwood J, Gallacher J, Ginnever RC. The relationship between heavy metals in garden soils and housedusts in an old

mining area of North Wales, Great Britain. Environ Pollut 1985; B9:255–66.
Dong A, Chesters G, Simsiman GV. Metal composition of soil, sediments, and urban dust and dirt samples from the Menomonee river watershed, Wisconsin, U.S.A. Water Air Soil Pollut 1984;22:257–75.
Driver JH, Whitmyre GK, Konz JJ. Soil adherence to human skin. Bull Environ Contam Toxicol 1989;43(6):814–20.
Farfel MR, Lees PS, Rohde CA, Lim BS, Bannon D, Chisolm Jr JJ. Comparison of a wipe and a vacuum collection method for the determination of lead in residential dusts. Environ Res 1994;65 (2):291–301.
Fergusson JE, Kim ND. Trace elements in street dust and house dusts: sources and speciation. Sci Total Environ 1991;100:125–50.
Fortune CR, Blanchard FT, Ellenson. Analysis of aged in-home carpeting to determine the distribution of pesticide residues between dust, carpet, and pad compartments. EPA/600/R-00/030. Research Triangle Park, NC 27711: National Exposure Research Laboratory, U.S. Environmental Protection Agency; 2000. p. 125.
Fry FA, Green N, Dodd NJ, Hammond DJ. Radionuclides in house dust. NRPB - R181. Chilton, Didcot, UK: National Radiological Protection Board; 1985.
HUD. National survey of lead and allergens in housing, final report. Analysis of lead hazards, vol. 1. Office of Lead Hazard Control, U.S. Department of Housing and Urban Development; 2001 [April].
Johnson DL. SAX characterization of particulate inclusions in biological tissue. Scan Electron Microsc 1983:1211–28 [1983/III].
Johnson D, Bretsch J. Soil lead and children's BLL Levels in Syracuse, NY, USA. Environ Geochem Health 2002;24 (4):375–85.
Johnson DL, McIntyre BL, Fortmann R, Stevens RK, Hanna RB. Chemical element comparison of individual particle analysis and bulk chemical analysis. Scan Electron Microsc 1981:469–76 [1983/I].
Lanphear BP, Matte TD, Rogers J, Clickner RP, Dietz B, Bornschein RL, et al. The Contribution of Lead-Contaminated House Dust and Residential Soil to Children's Blood Lead Levels A Pooled Analysis of 12 Epidemiologic Studies. Environ Res 1998;79 (1):51–68.
Laxen DPH, Lindsay F, Raab GM, Hunter R, Fell GS, Fulton M. The variability of lead in dusts within the homes of young children. Environ Geochem Health 1988;10(1):3–9.
Lewis RG, Fortmann RC, Camann DE. Evaluation of methods for monitoring the potential exposure of small children to pesticides in the residential environment. Arch Environ Contam Tox 1994;26: 37–46.
Lewis RG, Nishioka MG. Residential indoor exposure of children to pesticides following lawn applications. Proc Indoor Air 1999;2: 416–21.
Marcus AH, Elias RW. Estimating the contribution of lead-based paint to soil lead, dust lead and childhood blood lead. In: Beard ME, Iske SDA, editors. Lead in Paint, Soil and Dust: Health Risks, Exposure Studies, Control Measures, Measurement Methods, and Quality Assurance. ASTM STPPhiladelphia: American Society for Testing and Materials; 1995. p. 12–21.
Nishioka MG, Burkholder HM, Brinkman MC, Lewis RG. Distribution of 2,4-Dichlorophenoxyacetic acid in floor dust throughout homes following homeowner and commercial lawn applications: quantitative effects of children, pets and shoes. Environ Sci Technol 1999;33:1359–65.
Paustenbach DJ, Finley BL, Long TF. The critical role of house dust in understanding the hazards posed by contaminated soils. Int J Toxicol 1997;16:339–62.
Petrosyan V, von Braun MC, Spalinger SM, von Lindern IH. Seasonal variations of lead concentration and loading rates in residential house dust in northern Idaho. J Hazard Mater 2006;132:68–79.
Qian J, Shan QQ, Wang ZJ, Tu Q. Distribution and plant availability of heavy metals in different particle-size fractions of soil. Sci Total Environ 1996;187:131–41.
Rich DQ, Rhoads GG, Yiin LM, Zhang J, Bai Z, Adgate JL, et al. Comparison of home lead dust reduction techniques on hard surfaces: the New Jersey assessment of cleaning techniques trial. Environ Health Perspect 2004;110(9):889–93.
Roberts JW, Dickey P. Exposure of children to pollutants in house dust and indoor air. Rev Environ Contam Toxicol 1995;143:59–78.
Roberts JW, Camaan DE, Spittler TM. Reducing lead exposure from remodeling and soil track-in in older home. Air and waste management association paper 91-134.2, 84th annual meeting and exhibition, Vancouver, British Columbia, June 16–21; 1991.
Roberts JW, Crutcher ER, Crutcher ER, Glass G, Spittler TM. Quantitative analysis of road and carpet dust on shoes. Proc. Int. Specialty Conf. on Measurement of Toxic and Related Air Pollutants, May 7–9. Research Triangle Park, NC: Air and Waste Management Association; 1996. p. 829–35.
Roberts JW, Clifford WS, Glass G, Hummer PG. Reducing dust, lead, dust mites, bacteria, and fungi in carpets by vacuuming. Arch Environ Contam Toxicol 1999;36:477–84.
Rutz E, Valentine J, Eckart R, Yu A. Pilot study to determine levels of contamination in indoor dust resulting from contamination of soils. J Soil Contam 1997;6(5):525–36.
Spittler TM, Feder WA. A study of soil contamination and plant lead uptake in Boston Urban gardens. Commun Soil Sci Plant Anal 1979;10(9):1195–210.
Succop P, Bornschein R, Brown K, Tseng CY. An empirical comparison of lead exposure pathway models. Environ Health Perspect 1998;106(Suppl 6):1577–83.
Thornton I, Davies DJ, Watt JM, Quinn MJ. Lead exposure in young children from dust and soil in the United Kingdom. Environ Health Perspect 1990;89:55–60.
Thatcher TL, Layton DW. Deposition, resuspension, and penetration of particles within a residence. Atmos Environ 1995;13:1487–97.
Trowbridge PR, Burmaster DE. Parametric distribution for the fraction of outdoor soil in indoor dust. J Soil Contam 1997;6 (2):161–8.
U.S. Census Bureau. Summary File 1, GCT-P1. Urban/Rural and Metropolitan/Nonmetropolitan population; 2000. http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=01000US&-_box_head_nbr=GCT-P1&-ds_name=DEC_2000_SF1_U&-format=US-1, June 2006.
USEPA. Data Analysis of Lead in Soil and Dust, EPA/747/R-93/011. Washington, DC 20460: U.S. Environmental Protection Agency; 1993.
USEPA. Guidance Manual for the Integrated Exposure Uptake Biokinetic model for lead in Children U.S. Environmental Protection Agency, EPA/540/R-93/081, PB93-963510. Washington, DC 20460: U.S. Environmental Protection Agency; 1994.
USEPA. Exposure Factors Handbook. National Center for Environmental Assessment. Washington, DC 20460: U.S. Environmental Protection Agency; 1997.
USEPA. Child-Specific Exposure Factors Handbook. National Center for Environmental Assessment. Washington, DC 20460: U.S. Environmental Protection Agency; 2004.
Von Lindern IH, Spalinger SM, Bero BN, Petrosyan V, von Braun MC. The influence of soil remediation on lead in house dust. Sci Total Environ 2003;203:59–78.

Watt JM, Moorecroft S, Brooks K, Culbard E, Thornton I. Metal contamination in dusts and soils in urban and rural households in the United Kingdom. Trace Subst Environ Health 1983;17:229–35.
Yiin LM, Rhoads GG, Lioy PJ. Seasonal influences on childhood lead exposure. Environ Health Perspect 2000;108(2):177–82.
Yiin LM, Rhoads GG, Rich DQ, Zhang J, Bai Z, Adgate JL, et al. Comparison of techniques to reduce residential lead dust on carpet and upholstery: the New Jersey assessment of cleaning techniques trial. Environ Health Perspect 2002;110(12):1233–7.